A Morphological and Mineralogical Study of the Gray Hydromorphic Soils of the Hawaiian Islands[1]

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ABSTRACT: Gray hydromorphic soils are imperfectly to poorly drained soils that occur on the coastal fringes of the Hawaiian Islands on surfaces of Pleistocene to Recent age. Mottling is characteristic of the soils, and gley horizons occur in the more hydromorphic soils in the group. As the soils become hydromorphic, soil color values increase and structures deteriorate.

Halloysite is the dominant clay mineral in the less hydromorphic soils and montmorillonite is dominant in the more hydromorphic soils of the group. The montmorillonite is iron-rich and in one soil has the formula $(X_{0.74}K_{0.11})\ (Si_{7.52}Al_{0.48})^{IV}\ (Al_{1.85}Fe_{1.66}{}^{3+}Mg_{0.35}Ti_{0.10})^{VI}O_{20}(OH)_4$. Hydrated halloysite occurs in all the soils studied, but it is most abundant in the more hydromorphic soils. Although the soils are derived from different alluvial materials, the trend of increasing montmorillonite and increasing hydrated halloysite with increasing hydromorphism is clearly related to the pedogenic processes operating in the soils. Similar mineralogical trends are found with increasing depth in each soil.

GRAY HYDROMORPHIC SOILS in Hawaii are imperfectly to poorly drained soils that occur along the coastal fringes of the islands. They are formed from alluvium derived by erosion from the Low Humic Latosols that occur above them and from the surrounding hills.

Cline et al. (1955) classified these soils on the basis of the expression of hydromorphic characteristics in the profile. Gill and Sherman (1952), attempting to explain the poor physical properties of the soils, stated that they are always in a dispersed condition because the percentage of Mg^{++} ions in the exchange complex is high. They also noted that the soils had a high amount of 2:1 expanding type minerals. Jackson (1965), in dealing with the formation of minerals in lowland soils, noted that pedogenic montmorillonite frequently resulted from the influx into lowland areas of mineral colloids and solutions containing silicon, iron, aluminum, magnesium, calcium, and sodium ions.

This paper describes the morphological and mineralogical properties of a sequence of hydromorphic soils formed from calcareous and noncalcareous alluvia. Variations with respect to drainage are examined; the nature of the secondary minerals, their distribution, and the processes of their formation are commented upon.

SOILS STUDIED

Samples were taken from six soil series, delineated by Cline et al. (1955), which represented a range of hydromorphism. Brief profile descriptions are given in Table 1. The settings and sampling sites are described briefly below. Details of profile descriptions and sample location are given by Hussain (1967).

Honouliuli: The soil occurs on the Ewa clay plain (Ruhe et al., 1965) and is formed in noncalcareous alluvium derived from strongly weathered olivine basalts. Soils topographically above Honouliuli are highly kaolinic Low Humic Latosols. The profile sampled was from

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TABLE 1

BRIEF PROFILE DESCRIPTIONS OF GRAY HYDROMORPHIC SOILS STUDIED

HORIZON*	DEPTH (inches)	COLOR		STRUCTURE	MOTTLES
		MOIST	DRY		
Honouliuli clay					
Ap	0–24	5yr 3/2	5yr 3/1	mod f-m gr	—
B21	24–34	5yr 3/3	5yr 3/3	mod m sblky	—
B22	34–43	5yr 3/3	5yr 3/3	mod m sblky	—
C1	43–53	5yr 3/3	5yr 3/3	mod m sblky	—
C2	53–80	5yr 3/3	5yr 3/3	mod m sblky	rare
Pearl Harbor clay					
A1	0– 6	7.5yr 3/2	5yr 3/3	strong f-m gr	—
B21g	6–11	5yr 3/3	5yr 4/2	mod m sblky	many distinct
B22g	11–16	7.5yr 4/3	5yr 3/3	mod c blky	many distinct
IIC1g	16–23	10yr 4/3	10yr 4/4	structureless	common faint
IIC2g	23+	10yr 3/1	10yr 4/1	wk prism	common faint
Kalihi clay					
Ap1	0– 8	10yr 3/2	10yr 4/2	strong m gr	few faint
Ap2	8–16	10yr 2/3	10yr 4/2	strong c sblky	common faint
B21g	16–27	2.5yr 4/0	2.5yr 5/0	mod c sblky	common prominent
B22g	27–40	5yr 4/4	5yr 5/2	wk c blky	many prominent
C1g	40–54	2.5yr 5/0	2.5yr 6/0	structureless	—
C2g	54–60	2.5yr 6/0	2.5yr 5/0	structureless	—
IICg	60+	10yr 5/8	10yr 6/4	structureless	—
Laie clay					
Ap1	0– 4	10yr 3/1	10yr 3/2	strong f sblky	—
Ap2	4–12	10yr 3/1	10yr 3/1	strong f sblky	few distinct
B21g	12–20	5y 4/1	5y 5/1	wk m sblky	many prominent
B22g	20–27	5y 4/1	5y 5/1	wk prism	common prominent
B31g	27–35	5y 3/2	10yr 5/1	wk prism	few prominent
B32g	35–41	5gy 5/1	5y 5/1	wk gr	few distinct
B33g	41–48+	5y 5/1	5y 4/1	strong m gr	few faint
Kaloko clay					
Ap1	0– 6	5yr 3/3	5yr 4/3	mod m gr	few faint
Ap2	6–12	5yr 4/3	7.5yr 5/2	strong m sblky	few faint
B2	12–20	7.5yr 5/2	7.5yr 8/2	strong c sblky	common distinct
IICcag	20–29	7.5yr 8/4	2.5y 8/2	wk c gr	many prominent
IIIC1g	29–33	10G 6/1	2.5y 7/0	structureless	—
IIIC2g	33–43	10G 5/1	2.5y 7/0	structureless	—
IIIC3g	43+	10G 6/1	7.5yr 5/0	structureless	—
Nohili clay					
Ap1	0–14	5yr 3/3	7.5yr 4/2	wk c sblky	—
Ap2	14–22	5yr 3/3	5yr 4/3	structureless	—
B22	22–31	7.5yr 2/2	10yr 3/1	wk f sblky	—
IIC1g	31–37	5y 5/1	2.5y 7/0	wk f sblky	—
IIC2g	37–46	2.5y 5/2	2.5y 8/2	wk f sblky	—
IIICcag	46–55	2.5y 5/2	2.5y 8/0	structureless	—
IVCg	55–60+	5y 4/1	2.5y 7/0	structureless	—

* All horizons have clay texture except Pearl Harbor IIC1g, IIC2g; Kaloko IICcag, IIIC1g, IIIC3g; and Nohili IIICcag.

a Soil Conservation Service correlation site for the series and is considered to be modal.

Pearl Harbor: The soil occurs in a small area around the West Loch of Pearl Harbor. It lies below the Ewa clay plain and is probably formed from material derived from that plain and from embayed sediments from the harbor. The profile sampled was approximately 10 feet above sea level and is less hydromorphic than the modal profile for the series, which contains peat within the profile.

Kalihi: The soil occurs near sea level in the Mahaulepu Valley on Kauai in alluvium derived from soils on the slopes of Haupu caldera. The rocks from which the alluvium is derived may have been hydrothermally altered to some extent. The profile sampled was from one of the Soil Conservation Service correlation sites for the series and is considered to be modal.

Laie: The soil occupies a small area on the windward side of Oahu. The series described by Cline et al. (1955) is of very limited extent and has been deleted as a series from the most recent soil survey of the island. The soil body is included as a noncalcareous clay type in the Kaloko series. For the purposes of this paper the earlier series name is retained. The soil occurs on a low, late Pleistocene surface, in alluvium derived from the Kailua volcanics. Stearns and Vaksvik (1935) pointed out that these rocks are hydrothermally altered. The rocks are quartzose and chloritic, and have given rise to the quartz and talc in marine sediments in Kaneohe Bay (Moberly, 1963). The profile sampled was modal for the series described by Cline et al.

Kaloko: The soil occurs near sea level on the Mana Plain on the southwestern side of Kauai. It is formed in calcareous alluvium derived from strongly weathered basalt, and is deposited with calcium carbonate over marl in brackish water in a shallow inland bay. Coralline limestone underlies the marl. The profile sampled was from a Soil Conservation Service correlation site for the series and is considered modal.

Nohili: This soil also occurs on the Mana Plain on Kauai at a slightly higher elevation than the Kaloko soil, which it resembles. The coralline limestone is further below the surface of this soil than is the Kaloko. The profile sampled was from a Soil Conservation Service correlation site for the series and is considered modal.

METHODS OF ANALYSIS

A total of 38 soil samples were examined in detail. Coarse clay (2–0.2μ) and fine clay ($< 0.2\mu$) fractions were separated according to the methods of Jackson (1956), and each fraction was examined separately. Each soil sample was treated before separation, first with 0.3M sodium acetate and then with H_2O_2 to remove organic matter. All samples were deferrated four times by the method given by Aguilera and Jackson (1953) and boiled with 4 percent Na_2CO_3 to remove free Al_2O_3 and SiO_2.

The clay fractions were examined by X-ray, DTA, weight-loss on ignition, and chemical analysis. Techniques such as K-saturation, Mg-saturation, and orientation of clays on basal planes, along with heating treatments and glycolation when necessary, were used for X-ray identification of minerals. Differential thermal analyses were obtained on Mg-saturated powder samples, which had been crushed through a 100-mesh sieve and equilibrated at 58 percent relative humidity under reduced pressure for 48 hours.

Free iron oxides were determined by the method of Kilmer (1960), and total chemical analysis by the method of Shapiro and Brannock (1956, 1962). Cation exchange capacity was determined by washing the soil sample with *N* NH_4OAc several times, removing excess salt with methyl alcohol, and extracting the adsorbed NH_4^+ with 4 percent KCl. NH_3 was distilled from the extract in an alkaline medium, absorbed in 4 percent boric acid, and titrated with standard acid.

Estimates of minerals present in the clay fractions were made using X-ray diffraction, DTA, and heating-weight-loss data and adjusting the estimates obtained so that the chemical composition calculated from the estimated mineral composition agreed with the chemical composition determined experimentally. The formula for montmorillonite was calculated for the fine clay of a horizon of the Nohili soil in which this was the preponderant mineral, and, because the formula was very similar to others calculated for montmorillonites in Hawaii, it was used as a standard for all the soils in the study.

RESULTS

Changes in Morphology with Hydromorphism

Hues and values of the epipedons show little variation throughout the hydromorphic sequence. Chromas of the epipedons do not de-

TABLE 2

MINERALOGICAL COMPOSITIONS OF COARSE CLAY (2–0.2μ) FRACTIONS OF GRAY HYDROMORPHIC SOILS

HORIZON	MINERALS* (%)								COARSE CLAY (% of total clay)
	Hl	Hh	Mt	Il	Gb	Mg	Qr	Pl	
Honouliuli clay									
Ap	80		11	4	5				18
B21	59	7	21	4	8				17
B22	58	4	24	5	8				17
C1	75	7	18						18
C2	81	6	10		4				17
Pearl Harbor clay									
A1	47	8	11	11	14	9			15
B21g	60	9	18	4	8				12
B22g	58	11	21	2	7				21
IIC1g	64	9	21	4	4				19
IIC2g	46	3	43	2	4				27
Kalihi clay									
Ap1	32	7	50	10					5
Ap2	37	4	45	12					6
B21g	50	3	29	14					5
B22g	29	3	47	20					6
C1g	23	7	51	19					6
C2g	26	5	47	20					5
IICg	8	12	80						8
Laie clay									
Ap1	37		32	20	2		3	4	18
Ap2	39		35	17	2	2	4		19
B21g	38		52	7			2		24
B22g	16	8	57	6	2		2	8	21
B31g	14	9	60	2	66			8	20
B32g	220	8	67	2				3	23
B33g	17	6	70	3				4	24
Kaloko clay									
Ap1	19	12	69						18
Ap2	17	12	71						20
B2	17	14	69						21
IICcag	18	17	65						12
IIIC1g	13	15	72						12
IIIC2g	14	16	70						14
IIIC3g	12	14	73						20
Nohili clay									
Ap1	20	3	76						18
Ap2	21	3	76						24
B2	10	3	84				1	2	21
IIC1g	9	3	81		2		3	2	10
IIC2g	6	6	81		5			2	14
IIICcag	8	5	85		2				25
IVCg	10	5	80		2			2	27

* Mineralogical symbols: Hl, halloysite; Hh, hydrated halloysite; Mt, montmorillonite; Il, mica; Gb, gibbsite; Mg, magnetite; Qr, quartz; Pl, plagioclase feldspar.

crease with increasing wetness, as is suggested in the "7th Approximation" (U.S.D.A. Staff, 1960, 1967) for several soil groups affected by hydromorphism.

As a group, the soils are characterized by the presence of mottled or gley horizons, although the Honouliuli soil has only rare mottles. The coarsest and most prominent mottles are found in Pearl Harbor, Kalihi, and Laie soils, where the optimum combinations of fluctuating water table and secondary iron oxides occur. Gley horizons are found in Kalihi, Laie, Kaloko, and Nohili soils. In the upper Cg horizons of the Kaloko soil the typical color of gley remains on exposure to the air (irreversible gleying), while in the lowest Cg horizon of the same soil the color changes on exposure (reversible gleying). In explaining the causes of irreversible gleying, Bloomfield (1959) noted that gley horizons retaining no ferrous sulfide keep their gley color on exposure to the air, and the color becomes lighter when the soil becomes dry.

Structures in the epipedons are generally moderate to strong, fine or medium granular. The strongest, most granular structures occur in the middle soils of the sequence, decreasing to moderate granular in the Honouliuli soil and to weak coarse subangular blocky in the Nohili soil. In the subsurface horizons, the structure decreases from moderate, medium subangular blocky in Honouliuli to massive in the most hydromorphic soils.

All the soils have clay textures in the epipedons. Consistencies all tend to be hard when dry, firm when moist, sticky and plastic when wet, except for the marl-containing horizons of the Kaloko and Nohili soils, which are soft when dry and nonsticky when wet.

The Cg horizons of the Kaloko soil contain appreciable amounts of gypsum. These horizons are thin, but according to the definitions in the "7th Approximation" (U.S.D.A. Staff, 1960) they may be called *gypsic*. It is likely, however, that they were formed during the drying and oxidation of the saline marl after the sea retreated and are not related to later pedogenic processes. No gypsum occurs in the solum of any of these soils, which contrasts them with the Dark Magnesium Clays of Hawaii studied by Raymundo (1965).

TABLE 3

MINERALOGICAL COMPOSITIONS OF FINE CLAY ($< 0.2\mu$) FRACTIONS OF GRAY HYDROMORPHIC SOILS

HORIZON	MINERALS* (%) Hl	Hh	Mt
Honouliuli clay			
Ap	86		14
B21	84	1	15
B22	81		19
C1	78		22
C2	78		22
Pearl Harbor clay			
A1	83		17
B21g	81		19
B22g	80		20
IIC1g	72		27
IIC2g	61		39
Kalihi clay			
Ap1	70	2	30
Ap2	68	3	31
B21g	65	2	34
B22g	53	5	41
C1g	56	3	41
C2g	54	3	43
IICg	24	5	71
Laie clay			
Ap1	22	6	72
Ap2	22	6	72
B21g	20		75
B22g	23	5	72
B31g	20	6	75
B32g	15	5	80
B33g	16	5	79
Kaloko clay			
Ap1	19	8	73
Ap2	17	7	76
B2	16	8	76
IICcag	13	10	77
IIIC1g	10	9	81
IIIC2g	10	9	81
IIIC3g	9	8	82
Nohili clay			
Ap1	19	5	75
Ap2	18	6	75
B2	10	7	83
IIC1g	8	7	85
IIC2g	7	7	86
IIICcag	7	7	86
IVCg	8	8	84

* For key to mineralogical symbols see footnote to Table 2.

Clay Mineralogy

Figures for the mineralogical compositions of the coarse clays ($2–0.2\mu$) of all the soils are given in Table 2, and for the fine clays (0.2μ) in Table 3.

Honouliuli Clay

The dominant mineral in the clays of the Honouliuli soil is halloysite. In this respect the Honouliuli soil resembles the Low Humic Latosols which occur on older and higher surfaces, but it differs from them in that it also contains small to moderate amounts of montmorillonite. The coarse clays also contain gibbsite, which may be inherited from the parent alluvium.

In the fine clay fractions, halloysite content decreases and montmorillonite content increases with depth. This may be due (a) to the nature of the alluvium, (b) to the formation of montmorillonite at depth under the influence of calcium- and magnesium-rich soil solutions, or (c) to more intense weathering near the surface which has caused the destruction of montmorillonite and the formation of halloysite.

If the alluvium was originally kaolinic, that is, derived from the Low Humic Latosols, as appears likely, then montmorillonite must be forming in the soil. The age of the soil is 38,000 years (Ruhe et al., 1965), and the rate of montmorillonite formation, therefore, is 0.0004 grams per 100 grams of soil material per annum.

Pearl Harbor Clay

Dominant minerals in the clay fractions are halloysite, montmorillonite, hydrated halloysite, mica, and gibbsite. The montmorillonite content increases and the amounts of the other four minerals decrease with depth. There may be a small amount of siderite, not shown in the tables, in the lowest horizon of the soil.

Ruhe et al. (1965) gave the age of the surface in which this soil occurs as 670 ± 100 years. If the parent alluvium of soil was derived from the Honouliuli soil, and if, therefore, the amount of montmorillonite in it at soil-formation time zero was about 10 percent, the rate of montmorillonite formation in the soil is 0.328 grams per 100 grams of soil material per annum.

Kalihi Clay

The clay fractions together total more than 80 percent of this soil. In the coarse clay fraction, which constitutes only 5 percent of the total clay, halloysite and montmorillonite are the two dominant minerals. A moderate amount of mica in this fraction may be related to the hydrothermal action that has affected the soil parent material.

Halloysite is the dominant mineral in the fine clay fractions, except in the Cg horizon where a lithologic discontinuity occurs and montmorillonite is the dominant mineral. Above the discontinuity, the amount of montmorillonite increases with depth.

Laie Clay

The amounts of halloysite are high in the coarse clay fractions of the top three horizons of this soil. Montmorillonite content gradually increases with depth. The coarse clay fractions also contain mica, which decreases with depth, and small amounts of gibbsite, quartz (mainly in the upper horizons), and plagioclase feldspar (mainly in the lower horizons). It has already been pointed out that this soil was formed from hydrothermally altered, quartz-chlorite-containing rocks.

Montmorillonite is the dominant mineral in the fine clay fractions. Its distribution is nearly uniform throughout the profile. Halloysite and hydrated halloysite are also present, the latter mainly in the lower horizons.

Kaloko Clay

The clay fractions of this soil contain only montmorillonite, halloysite, and hydrated halloysite. In the fine clays, montmorillonite increases with depth from 73 percent in the Ap1 horizon to 82 percent in the IIIC3g horizon. Chemical analyses indicate that the montmorillonite is iron-rich.

Nohili Clay

Montmorillonite is the dominant mineral in the clay fractions of this soil. Halloysite content is moderate to low throughout. A structural formula for the montmorillonite is in the fine clay fraction of the IIICcag horizon was calculated from the chemical analysis and the cation exchange capacity, after allowing for the small amounts of other minerals and following the method of Kelley (1945), and Sawnhey and Jackson (1958). The formula is:

$$(X_{0.74}K_{0.11})\ (Si_{7.52}Al_{0.48})^{IV}$$
$$(Al_{1.85}Fe_{1.66}{}^{3+}Mg_{0.35}Ti_{0.10})^{VI}O_{20}(OH)_4.$$

Sawnhey and Jackson (1958) and Sherman et al. (1962) obtained similar formulas for montmorillonites in Hawaii.

For this mineral the net charge deficit per unit cell is 0.85 equivalent. More than half of the exchange charge originates in the tetrahedral layer. The mineral has a unit cell weight of 788.6, the calculated surface area is 720 m^2/gm, and the surface charge density, calculated from this and the cation exchange capacity of 94 meq/100 gm, is 13.0×10^{-6} coulombs/cm^2.

DISCUSSION

Stages of Hydromorphism

In soils affected by hydromorphism (a) ferric, manganic, and sulfate ions are reduced and dissolved and sometimes form complexes with organic molecules, and (b) the reduced and dissolved ions and complexes are washed out of the profile. These processes together resemble to some extent the process of cheluviation (Swindale and Jackson, 1956) except that in the latter, reduction is not a necessary condition.

When the hydromorphism is slight, the ions that are reduced are moved mostly within the profile by the fluctuating water table, and mottles and soft concretions are produced by precipitation and reoxidation. With stronger hydromorphism, the reduction is more complete, and characteristic pale greenish or bluish gray gley horizons are produced. With the strongest hydromorphic effects, virtually all the reduced ions are removed from the gley horizon, and the horizon does not increase in color on oxidation.

The Honouliuli soil has no gley horizon and almost no mottles, and it must therefore be considered to be transitional between the Gray Hydromorphic soils and the Low Humic Latosols. The Pearl Harbor soil, which, it should be remembered, is considered to be less hydromorphic than the modal profile for the Pearl Harbor series, has distinct mottling in the upper horizons, and has a strongly gleyed horizon below 23 inches which is still too brownish in color and has too much structure to be a gley horizon as this has been defined (Zavalishin, 1928; Rode, 1962). The other four soils all have gley horizons. In the Nohili soil, which is the most hydromorphic, two of the gley horizons do not increase in color on oxidation.

Mineralogical Changes in the Gray Hydromorphic Soils

The mineralogical compositions of the clay fractions ($<2\mu$) of the six gray hydromorphic soils are given together in Table 4. The important facts may be summarized as follows: (1) In all the soils there is a decrease in halloysite down the profile and an increase in montmorillonite, (2) hydrated halloysite content increases with depth, and (3) the amount of montmorillonite increases and that of halloysite decreases with increasing hydromorphism (Fig. 1).

The soils are formed from alluvium derived in the main from kaolinic (and mostly halloysitic) soils at higher elevations. This alluvium has been altered during deposition and by pedogenic processes associated with hydromorphism, with modifications due to differences in the original parent materials.

DEPOSITIONAL PROCESSES: Much of the alluvium was deposited on shallow coastal benches and has been affected by seawater. Because kaolin minerals are stable in most seawater compositions (Biscaye, 1965; Swindale and Fan, 1967), this would not lead to major changes in mineralogy unless the seawater were highly calcareous, when montmorillonite should form slowly. This seems to have occurred during deposition of the alluvium on the Mana Plain, from which the Kaloko and Nohili soils are derived. However, the results of extensive investigations by Biscaye (1965) and more recent work by Swindale and Fan (1967) around the coasts of Hawaii suggest that relatively small amounts of montmorillonite have been produced in this way. Because the rates of formation of the montmorillonite where it is formed are likely to be much lower than the rates of deposition of the sediment, the amounts of montmorillonite should decrease from the bottom to the top of the sediments, that is, to increase down the profile when the sediment becomes a soil. This is the pattern shown in these soils.

The alluvium in which the Laie soil is formed was derived from hydrothermally altered basalts which contain mica, quartz, and chlorite. The first two minerals remain in the Laie soil (see Table 4), but the chlorite has probably been altered to montmorillonite.

PEDOGENIC PROCESSES: Montmorillonite can be produced by pedogenic processes in hydromorphic soils because an influx of colloids and ions of silicon, iron, aluminum, magnesium, calcium, sodium, and potassium is continually taking place into the lower horizon in the water

TABLE 4

MINERALOGICAL COMPOSITIONS OF THE CLAY FRACTIONS ($< 2\mu$) OF GRAY HYDROMORPHIC SOILS

	MINERALS* (%)								
HORIZON	Hl	Hh	Mt	Il	Gb	Mg	Qr	Pl	TOTAL
Honouliuli clay									
Ap	85		13	1	1				100
B21	80	1	16	1	1				99
B22	77	1	20	1	2				101
C1	77	1	21						99
C2	79	1	20						100
Pearl Harbor									
A1	78	1	16	1	2	1			99
B21g	77	1	19	1	1				99
B22g	75	2	20	1	2				100
IIC1g	70	2	26	1	1				100
IIC2g	56	1	40	1	1				99
Kalihi clay									
Ap1	68	2	31	1			1		102
Ap2	66	3	32	1					102
B21g	64	2	34	1					101
B22g	52	5	42	1					100
C1g	54	3	42	1					100
C2g	52	3	43	1					99
IICg	23	6	71						100
Laie clay									
Ap1	29		66	4	1				102
Ap2	29		66	3	1	1	1		101
B21g	28		69	2			1		100
B22g	24	4	69	1			1	2	102
B31g	19	7	72	1	1			2	101
B32g	17	6	77					1	101
B33g	16	6	77	1				1	101
Kaloko clay									
Ap1	18	8	72						98
Ap2	17	8	75						100
B22	16	9	74						99
IICcag	13	11	76						100
IIIC1g	11	10	80						101
IIIC2g	11	10	80						101
IIIC3g	9	9	81						99
Nohili clay									
Ap1	20	5	76						101
Ap2	19	6	75						100
B22	10	6	84					1	101
IIC1g	8	6	84						98
IIC2g	7	7	85		1				100
IIICcag	7	5	86		1				100
IVCg	9	7	83		1			1	101

* For key to mineralogical symbols see footnote to Table 2.

table. Halloysite previously formed in base-poor, well-drained environments in the Low Humic Latosols may become unstable, and montmorillonite may be produced (Mohr and Van Baren, 1959; Brewer, 1964; Swindale, 1966).

The amount of montmorillonite should increase with depth in the profile because the changes will occur in any horizon only while the water table is present. Resilication may occur as follows (modified from Jackson, 1965):

1. gibbsite $\xrightarrow[\text{at low pH}]{\text{resilication}}$ halloysite $\xrightarrow[\text{at high pH}]{\text{resilication}}$ montmorillonite

2. gibbsite $\xrightarrow[\text{high pH + high base status}]{\text{resilication at}}$ montmorillonite

When the activity of iron in the soil solutions is sufficiently high, this element will enter the lattice of the crystallizing montmorillonite to produce nontronite. This seems to have occurred in these soils. The evidence is the nontronite formula obtained for the montmorillonite in the Nohili soil (see above), and the highly significant correlation between total Fe_2O_3 and amounts of montmorillonite in the fine clays (Fig. 2).

The increase in hydrated halloysite with depth, presumably at the expense of halloysite, is a common feature of Hawaiian soils formed from alluvium or residuum. It has been recorded previously in unpublished M.S. theses (for example, by Saing, 1965, and by Kimura, 1965*) and in much other unpublished work. Swindale and Jackson (1960) recorded a similar change in soils from rhyolite residuum in New Zealand, and they ascribed it to the moister conditions and less frequent wetting and drying cycles with increasing depth in the soil.

Pedogenic effects similar to those observed with increasing depths in a single soil occur in the range of soils with increasing hydromorphism. Halloysite decreases and montmorillonite increases from Honouliuli to Nohili (Fig. 1). The ratio of halloysite to hydrated halloysite decreases from 80 in Honouliuli to approximately 1 in Nohili (Table 4). After taking full account of the depositional processes considered above, it is clear that the relationships halloysite/montmorillonite and halloysite/hy-

* Both at the University of Hawaii.

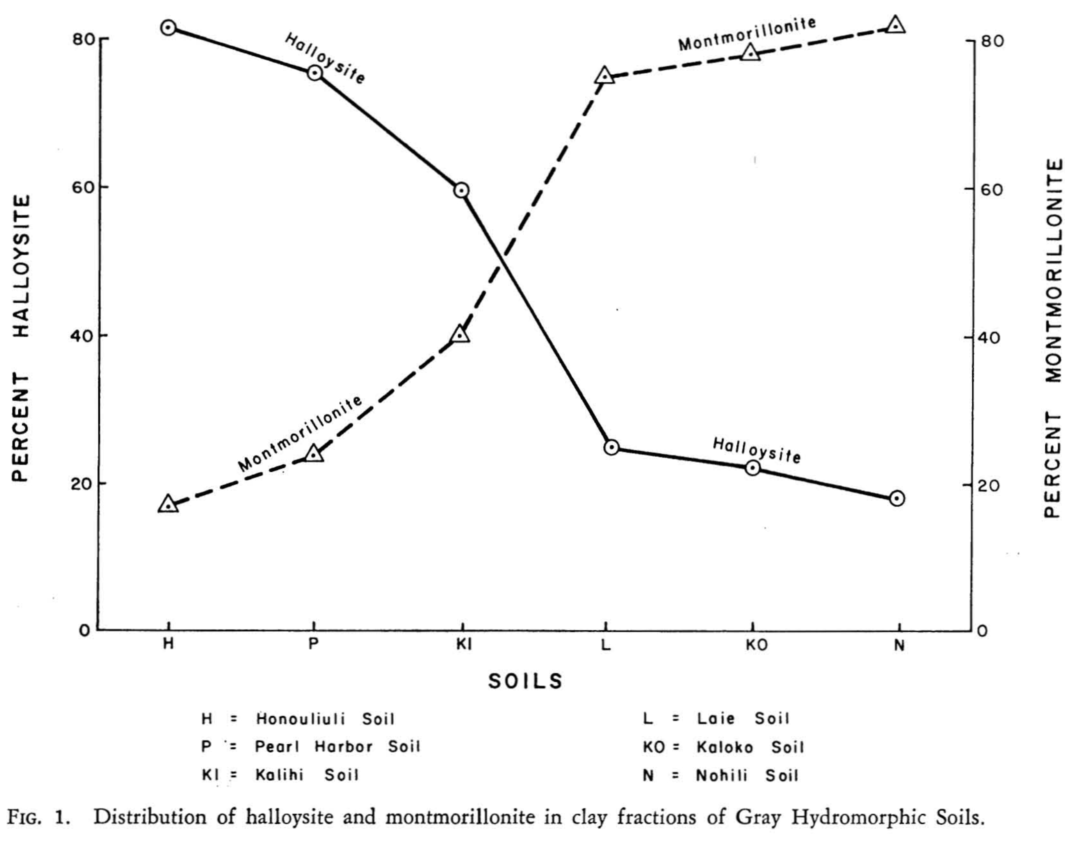

FIG. 1. Distribution of halloysite and montmorillonite in clay fractions of Gray Hydromorphic Soils.

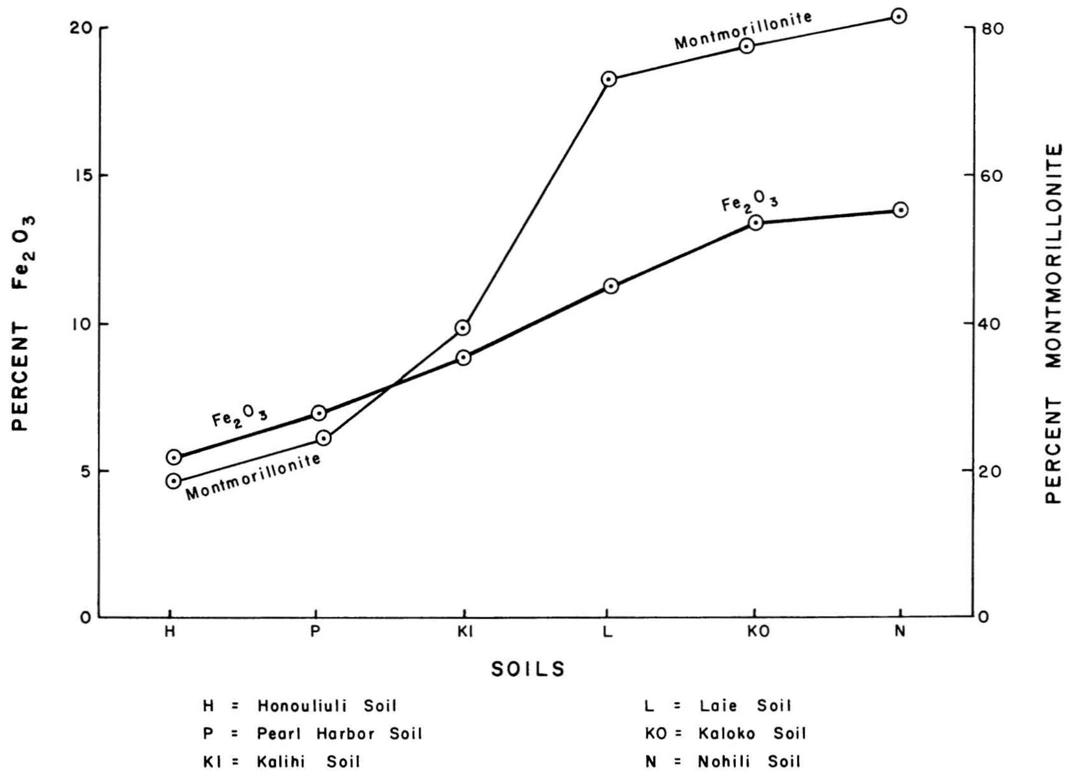

FIG. 2. Distribution of total Fe_2O_3 and montmorillonite in fine clay fractions of Gray Hydromorphic Soils.

drated halloysite are related to pedogenic processes.

Technical Classification of the Soils

The classifications given in Table 5 are based upon the "7th Approximation" and its March 1967 supplement. The classifications given for all profiles except Pearl Harbor and Laie, which are nonmodal profiles, are the official SCS classification of the series (Soil Classification System—Placement of Series, West Region, July 1968/U.S.D.A. S.C.S.). In this classification the soils are no longer classified in a single group, although the first four are in the same order. The classification for all soils satisfactorily indicates their hydromorphic character—with Honouliuli correctly excluded from the aquic suborders of the Inceptisols—and indicates further the increasing hydromorphism of the first three soils. The classification of the Laie soil departs slightly from this sequence because of the much higher amounts of montmorillonite the soil contains, related only in part to the effect of increasing hydromorphism. The classifications of Kaloko and Nohili soils are consequences of the underlying calcareous parent materials, and the sequential hydromorphic relationship is no longer obvious.

TABLE 5

TECHNICAL CLASSIFICATION AT THE SUBGROUP LEVEL OF THE GRAY HYDROMORPHIC SOILS SAMPLED

SOIL	SUBGROUP IN CLASSIFICATION
Honouliuli	Vertic Ustropepts*
Pearl Harbor	Aeric Tropaquepts
Kalihi	Typic Tropaquepts
Laie	Vertic Tropaquepts
Kaloko	Aquic Rendolls
Nohili	Cumulic Haplaquolls

SOURCE: U.S.D.A. Staff, 1960, 1967.

Now Typic Chromustert.

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